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# Energy transition under irreversibility: a two-sector approach\*

Prudence Dato<sup>†</sup>

July 6, 2015

## Abstract

In this paper, we analyze the optimal energy transition of a two-sector economy (energy and final goods) with exhaustible oil reserves, a renewable source of energy and a pollution threat. The latter corresponds to a pollution threshold above which a part of the capital is lost (following flooding for instance). We show that the optimal energy transition path may correspond to a corner regime in which the economy starts using both resources, then crosses the pollution threshold and therefore loses a part of its capital. At the end, the sole adoption of the renewable energy is optimal only in the long run. This result is in line with the asymptotic energy transition arguments stating that the transition to "clean" energy may happen only in the long run. We also show that economy reduces the use of energy resource as long as the productivity of capital and energy services is high. Therefore, public policies should promote investments in energy innovation that targets productive sector, home appliances and buildings and helps to save both money and energy. We extend the present model to allow for additional investment in energy saving technologies. Our main results show that this additional investment favours the energy transition in the sense that it increases the time within which the economy may experience the catastrophe and the welfare of the society. For policy implications, economic instruments such as taxes on "dirty" energy, subsidies on "clean" energy or incentives for energy saving technologies need to be implemented in order to promote the energy transition. This is particularly important for developing countries that mostly rely on polluting energy resources and are the most vulnerable to climate change. But those economic instruments should be carefully designed in line with the asymptotic energy transition result.

**Keywords:** *energy, irreversibility, pollution, switch.*

**JEL Classification:** *Q30, Q53, C61.*

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# 1 Introduction

In order to reduce global CO<sub>2</sub> emissions up to 50 per cent from 2005 to 2050, several energy policies use scenarios that mostly include the adoption of renewable energy (RE) sources and investments in energy saving technologies (EST). Despite the growing investments in the production of RE (63 to 244 billion USD from 2006 to 2012 (GEA, 2012)), fossil fuels as "dirty" energy are still mainly used (78.2%) throughout the world. Therefore it becomes crucial not only to drastically change the way energy is produced, but to also look for energy saving strategies. According to the efficiency pathways of the Global Energy Assessment (GEA), about one-third of overall investment in the energy sector is efficiency related (GEA, 2012). This paper focuses on the issue of energy transition that involves both the decision of RE adoption and that of the investment in EST. We analyze the optimal energy transition of a two-sector economy (energy and final goods) with exhaustible oil reserves, a renewable source of energy and a pollution threat.

The issue of energy transition involves both the decision of RE adoption and that of the investment in EST. The former decision concerns an adoption of "clean" energy sources as an alternative that could replace the consumption of polluting sources of energy, while the latter could help reduce overall energy consumption. At the beginning of the literature on natural resource economics, many authors provided a different focus on the long run depletion of oil reserves and on the polluting feature of oil. Dasgupta and Heal (1974, 1979), Dasgupta and Stiglitz (1981) and Krautkraemer (1986) analyze the long run depletion of oil reserves, while Nordhaus (1994) and Tahvonen (1996, 1997) focus on the polluting aspects of oil. In this regard, one solution could be to adopt a backstop technology (a renewable resource for instance) as a clean energy. More recently, several works (Acemoglu et al., 2014; Amigues et al., 2013 and Tsur and Zemel, 2003) focus on climate change issues as one of the important reasons that encourage the transition to clean energy or to clean technologies. As the use of polluting energy resource generates pollution that accumulates over time, the ecological catastrophe may occur at some point in time. The catastrophic event will generate some damage that can be irreversible<sup>1</sup> (Forster, 1975; Tahvonen and Withagen, 1996; Ulph and Ulph, 1997; Pindyck, 2002; Pommeret and Prieur, 2009 and Ayong Le Kama et al., 2011). It can also be partly reversible (Tsur and Zemel, 1996 and Naevdal, 2006), or fully reversible (Kollenbach, 2013).

There is no consensus in the literature about how to model environmental damage due to pollution. Some authors consider the damages as income loss (Karp and Tsur, 2011 and Tsur and Withagen, 2012) or social welfare loss (Van der Ploeg and Withagen, 2012 and Prieur et al., 2013). Other authors focus on productive sectors: capital loss (Horii and Ikefuji, 2010); or destruction capacity (Golosov et al., 2011). The present paper assumes that the economy experiences a catastrophic event (flooding for instance)

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<sup>1</sup>There are various types of irreversibility. It can be an exhaustion of the natural capacity of regeneration (Tsur and Withagen, 2013), an irreversibility in the decision process (Pommeret and Prieur, 2009 and Ayong Le Kama et al., 2011) or a ceiling on the pollution stock (Lafforgue et al., 2008 and Chakravorty et al., 2012).

when the level of pollution is above a certain critical threshold. Therefore, the economy loses part of its productive stock of capital. Moreover, to support the simultaneous use of both resources, many authors assume a convexity of the production cost of renewable energy (Chakravorty et al., 1997 and Amigues et al., 2013) or an increasing extraction cost of fossil fuels (Tsur and Zemel, 2005 and Kollenbach, 2013). For instance, Amigues et al. (2013) study energy transition in a deterministic framework and consider adjustment costs over production capacity of renewable energy. They identify three energy regimes in a partial equilibrium setting with an intermediate regime of simultaneous use of both resources. In addition, several studies assume imperfect or perfect substitution between inputs. Alternatively, we consider the case of an economy with rigidities such that oil and RE sources are complementary as in Pelli (2012). Moreover, we also assume that capital use and energy are complementary, as in Pindyck and Rotemberg (1983), Boucekine and Pommeret (2004) or Diaz and Puch (2013).

In a deterministic framework, Boucekine et al. (2013) provide first order optimality conditions in an optimal regime switching problem with threshold effects. These optimality conditions are the continuity of appropriate co-states and states variables, and that of the Hamiltonian. The present paper is mainly related to the application in Boucekine et al. (2013) as it involves both the switching decision to cleaner energy sources and the pollution threshold effect as the main drivers of energy transition. However, the contribution of our paper is threefold. First, we use a two-sector approach in which the economy requires capital to produce energy that can be used as inputs to produce a final good. We do not allow a natural regeneration capacity, instead we consider the irreversibility of pollution for a loss of capital. In the same vein, we do not account for direct pollution damage, but only the loss of productive capital due to the occurrence of the catastrophe. In contrast to Boucekine et al. (2013), we allow a simultaneous use of both resources ("dirty" and "clean" energies). More precisely, we assume that there is a complementarity between both resource use and capital in the production of final goods.

Second we numerically show that the optimal energy transition path may correspond to a corner regime in which the economy starts using both resources, crosses the pollution threshold by losing a part of its capital and never adopts only renewable energy. This result is in line with the asymptotic energy transition argument that states that the transition to "clean" energy may happen only in the long run. For policy implications, economic instruments such as taxes on "dirty" energy and subsidies on "clean" energy need to be implemented in order to promote the energy transition. But those economic instruments should be carefully designed in line with the asymptotic energy transition result. Sensitivity analysis also shows that economy reduces the use of energy resource as long as the productivity of capital and energy services is high. Therefore, public policies should promote investments in energy innovation that targets productive sector, home appliances and buildings and helps to save both money and energy.

Third, we extend our model to the adoption of energy saving technologies. Very few works deal with the adoption of energy saving technologies (Charlier et al., 2011; De

Groot et al., 2001 and Acemoglu et al., 2012). In order to fill this gap in the literature about the importance of EST in energy transition, we extend our model to allow for investment decisions in EST. More precisely, the economy may decide to invest in energy saving appliances or in energy efficient systems to reduce overall energy consumption. This investment is additional to that made in clean energy to help reach the energy transition targets. Numerical results mainly show that this additional investment favours the energy transition in the sense that it increases the time within which the economy may experience the catastrophe and the welfare of the society. It is then profitable to design economic instruments that jointly target the promotion of "clean" energy and incentives for investment in energy saving technologies. This is particularly important for developing countries that mostly rely on polluting energy resources and are the most vulnerable to climate change. The remainder of this paper is structured as follows. The model is presented in Section 2. We analyze the optimal energy transition path in Section 3. Section 4 extends the model to allow investment in EST. Finally, we conclude in Section 5.

## 2 Model

We consider a closed economy that produces energy and final goods in a general equilibrium setting. The economy uses a "dirty" source (exhaustible oil reserves) and a "clean" source (solar panels) to produce energy. Part of the energy is used as energy services by a representative consumer through a CRRA utility function. The other part is used as input in a Leontief production function to produce final goods. The use of "dirty" energy by both final goods sector and households has a negative impact on the environment. Above a certain pollution threshold, the economy experiences a catastrophic event (following flooding for instance) and loses a part of its stock of capital. In the following sections, we describe the energy sector, the final good sector, households' utility and pollution threats, respectively.

### 2.1 Energy sector

Energy is an intermediate good that is produced using  $E_s$ , a non-renewable and "dirty" source, and  $E_x$ , a renewable and "clean" source. A representative consumer uses part  $E_2$  of the energy as energy services, while the other part  $E_1$  is used as input to produce final goods. Let us denote respectively  $E_{2s}$ ,  $E_{2x}$ ,  $E_{1s}$  and  $E_{1x}$  the parts of the NRE and RE that households use and that the final goods sector uses. We assume that the production of the NRE is costless. The stock  $S_t$  of the NRE at each time  $t$  is generated by the following dynamics:

$$dS_t = -E_{st}dt \quad (1)$$

where  $E_{st}$  is the rate of extraction of the NRE.

The production of RE requires the use of capital. For instance, to produce solar (respectively wind) energy, one needs to install some solar panels (respectively wind

turbines) in order to transform solar (respectively wind) into electricity. Hence we assume a " $\varphi$ -to-one" transformation of  $K_1$ , a part  $\phi$  of capital  $K$  as follows:

$$E_x = \varphi K_1 = \varphi \phi K \quad (2)$$

where  $\varphi$  is the productivity of capital in the RE sector and is greater than one ( $\varphi > 1$ ).

In our model, pollution only comes from the use of "dirty" energy. The following energy market clearing conditions holds.

The NRE that the economy produces is fully used as consumption by households and as input to produce final goods:

$$E_{st} = E_{1st} + E_{2st}. \quad (3)$$

The total production of the RE is split into the final goods sector and the household energy consumption:

$$E_{xt} = E_{1xt} + E_{2xt}. \quad (4)$$

Finally, the total energy that is used in the economy is that from the NRE and the RE:

$$E_{1t} + E_{2t} = E_{xt} + E_{st}. \quad (5)$$

## 2.2 Pollution threat

The use of the NRE either as consumption by household or as inputs to produce final goods generates GHG emissions. Pollution accumulates in the environment (atmosphere) according to the following process:

$$\dot{Z}_t = E_{st}. \quad (6)$$

We do not account for the natural regeneration capacity of environment as in Van der Ploeg and Withagen (2012, 2014). This can be seen as the most pessimistic way to deal with the threat of pollution to justify the necessity of an energy transition. Moreover, the economy experiences a catastrophic event (flooding for instance). When the level of pollution  $Z_t$  is above a certain critical threshold  $\bar{Z}$ , the economy loses a part  $\theta$  of its capital stock.

## 2.3 Final good sector

In order to produce a final good  $Y$ , a part  $E_1 = E_{1st} + E_{1xt}$  of energy and a part  $1 - \phi$  of capital ( $K_2$ ) serve as inputs in a Leontief production function. The interpretation runs as follows. There exist operating costs whose size depends on the energy requirement of the capital, such that to any capital use there corresponds a given energy requirement. Such a complementarity is assumed in order to be consistent with several studies arguing that capital and energy are complements (see for instance Berndt and Wood, 1974; Pindyck and Rotemberg, 1983; and more recently Diaz and Puch, 2013). The production function is defined as:

$$Y = \min\{\alpha_2 K_2, \beta_2 E_{1t}\} \quad (7)$$

with  $K_2 = (1 - \phi)K$ .

Additionally, we assume that both oil and the renewable resource use are complementary. Two types of justifications can be provided. First, using an econometric approach, Pelli (2012) proves that there exists some complementarity between the "dirty" sources of energy (oil, coal, gases) and the "clean" ones (hydroelectric, biomass-wood and waste, geothermal, solar/photovoltaic, wind and nuclear). The intuition is that the production of energy using RE source, for instance through solar panels, requires oil to build the solar panels. Second, the presence of rigidities in a macroeconomic view may also explain this complementarity between the oil and RE source: it is not easy to substitute between oil and electricity provided by solar panels. We define  $E_{1t}$  as:

$$E_{1t} = \min\left\{\frac{1}{\xi}E_{1st}, E_{1xt}\right\} \quad (8)$$

where  $\xi$  is the part of the NRE used in the energy mix.

## 2.4 Households

We consider a representative household using the energy services  $E_2$  and that consumes a non-energy good  $C$ . The utility  $U$  represents the consumer's preferences that are expressed by the expected discounted sum of instantaneous CRRA utility flows:

$$U = \int_0^{\infty} u(C_t, E_{2t})e^{-\rho t} dt \quad (9)$$

and

$$u = \frac{C_t^{1-\delta}}{1-\delta} + \frac{E_{2t}^{1-\delta}}{1-\delta} \quad (10)$$

where  $\rho$  is the discount rate and  $\delta$  is the coefficient of relative risk aversion that is different from 1.

Both RE and NRE are complementary for the same reasons as in the final goods sector:

$$E_{2t} = \min\left\{\frac{1}{\xi}E_{2st}, E_{2xt}\right\} \quad (11)$$

where  $\xi$  is the part of the NRE used in the energy mix.

Households own firms in both the energy and final goods sectors. They consume a part of the final good production and invest the rest to produce clean energy and final goods:

$$Y_t = C_t + \dot{K}_{1t} + \dot{K}_{2t}. \quad (12)$$

In the following sections, we first analyze the optimal energy transition path. In Section 4, we provide the numerical results. Finally, we extend the model to the adoption of energy saving technologies in Section 5.

### 3 Optimal energy transition path

In this section, we first analyze the general energy transition path that includes the energy regime switch and the occurrence of a catastrophic event. Three regimes can occur that correspond to the energy transition path. In the first, energy is produced by both oil and the renewable resource that are complementary, and the level of pollution is below the threshold. In the second regime, both energy sources are used again but pollution is above the threshold. Only renewable resources are used in the third regime. The second part of this section focuses on corner regimes as specific cases that we compare to the general energy transition path to isolate the optimal path. We exclude four corner regimes among a total of eight corner regimes because they are unfeasible. The regimes of  $T_1 = 0$  combined with  $T_2 > 0$ ,  $T_2 = 0$  or  $T_2 = \infty$  cannot occur because the economy cannot start above the pollution threshold without consuming the polluting energy. If the economy starts with a RE, it will never cross the pollution threshold as the RE is a "clean" energy. Thus, the regime that corresponds to the case  $T_2 = 0$  and  $T_1 > 0$  is not possible. Finally, we work with the following corner regimes. The economy only switches on the energy regime ( $T_1 = \infty$ ), the pollution regime ( $T_2 = \infty$ ), or the economy never switches ( $T_1 = \infty$  and  $T_2 = \infty$ ). The economy can also start with the RE and never switches on the pollution regime ( $T_1 = \infty$  and  $T_2 = 0$ ). In the last part of this section, we numerically solve for the optimal switching time associated with these corner regimes and the general regime, and provide the corresponding value function.

#### 3.1 General energy transition path

In this section, we analyze the general energy transition path that is described as the following. The economy starts using both sources of energy (RE and NRE) and therefore starts polluting. The economy accumulates the pollution up to the threshold  $\bar{Z}$ . Once the level of pollution exceeds this critical level  $\bar{Z}$ , the economy experiences a catastrophic event that could be a flooding, for instance. The economy still uses both sources of energy before completely switching to the sole use of the "clean" energy. We backward solve for the optimal general path by starting from the third regime (sole use of RE) that is followed by the second regime and lastly by the first regime. We use the boundary conditions as in Boucekkine et al. (2013) to find the optimal time at which the economy will cross the critical pollution threshold and will turn to "clean" energy only. As it is not possible to get an analytical solution, we solve it numerically.

##### 3.1.1 Third energy regime (RE, $\bar{Z}$ )

During the third regime, the economy is no longer polluting because it stops using the "dirty" energy source. The "clean" energy is the only available energy sources in the economy. Therefore, constraints on pollution accumulation and on NRE accumulation both become irrelevant. The economy has already crossed the critical pollution threshold and therefore still faces the negative consequences of the catastrophe. In this case, the social planner maximizes the sum of discounted utility subject to the constraint of capital accumulation.



The fact that the capital is split into final goods sector ( $K_{2t}$ ) and "clean" energy sector ( $K_{1t}$ ), together with the "Leontief conditions" in the final goods sector, help in deducing the following equation of capital accumulation (see the proof in Appendix A):

$$\dot{K} = \alpha_2(K - \frac{1}{\varphi}E_1 - \frac{1}{\varphi}E_2) - C.$$

The social planner solves the following programme:

$$\begin{aligned} V_3 &= \text{Max} \int_{T_2}^{\infty} (\frac{C^{1-\delta}}{1-\delta} + \frac{E_2^{1-\delta}}{1-\delta}) e^{-\rho(t-T_2)} dt \\ \text{st } \dot{K} &= \alpha_2(K - \frac{1}{\varphi}E_1 - \frac{1}{\varphi}E_2) - C. \end{aligned}$$

The first order conditions (FOCs) with respect to  $C$ ,  $E_2$  and  $K$  respectively give:

$$C^{-\delta} = \lambda \quad (13)$$

$$E_2^{-\delta} = \frac{\alpha_2}{\varphi} \lambda \quad (14)$$

and

$$\frac{\dot{\lambda}}{\lambda} = \rho - \alpha_2. \quad (15)$$

One can easily identify the consumption versus savings arbitrage condition in equations (13) and (14). It states that the marginal value of capital has to equal the marginal utility of consumption on the one hand and the marginal utility of energy services on the other hand. Moreover, condition (15) implies a constant instantaneous return over capital.

As energy services  $E_1$  and capital  $K_2$  are complementary in the final goods sector, we obtain:

$$Y = \alpha_2(K - \frac{1}{\varphi}E_1 - \frac{1}{\varphi}E_2) = \beta_2 E_1. \quad (16)$$

Solving the equation of capital accumulation by using equations (13)-(16) and the transversality condition (see the proof in Appendix B), we obtain:

$$K_t = -\frac{\Theta\delta}{\alpha_2 - \rho - \delta\Lambda} \lambda_{T_2}^{-\frac{1}{\delta}} e^{(\frac{\alpha_2 - \rho}{\delta})(t-T_2)},$$

where the unknown  $\lambda_{T_2}$  will be determined in Section 3.1.4 by using boundary conditions. We can easily deduce the value function  $V_3$  during the third regime:

$$V_3 = -\frac{\delta[1 + (\frac{\alpha_2}{\varphi})^{-\frac{1-\delta}{\delta}}] \lambda_{T_2}^{-\frac{1-\delta}{\delta}}}{(1-\delta)[\alpha_2(1-\delta) - \rho]}.$$

### 3.1.2 Second energy regime (NRE-RE, $\bar{Z}$ )

The economy uses both RE and NRE sources in the second energy regime. Despite the use of the "dirty" energy, the constraint on pollution accumulation is irrelevant because the economy has already crossed the critical pollution threshold. The economy starts facing damages from the catastrophe that has occurred. The social planner maximizes the sum of the discounted post event utilities and the discounted value function of the third regime subject to constraints on capital accumulation and on NRE accumulation.

By using  $Y = \alpha_2 K_2$  because of "Leontief conditions" and  $K_2 = (1 - \phi)K$ , the equation of capital accumulation becomes:

$$\dot{K} = \alpha_2(1 - \phi)K - C.$$

The complementarity between the NRE and the RE, respectively gives that:

$E_{1t} = \frac{1}{\xi} E_{1st} = E_{1xt}$  and  $E_{2t} = \frac{1}{\xi} E_{2st} = E_{2xt}$ . This implies that  $E_{1st} = \xi E_{1t}$ , and  $E_{2st} = \xi E_{2t}$ . By summing up the two precedent expressions, we get that  $E_{st} = \xi(E_{1t} + E_{2t})$ . The latter expression in (1) gives:

$$\dot{S}_t = -E_{st} = -\xi(E_{1t} + E_{2t}).$$

The social planner solves the following programme:

$$\begin{aligned} V_2 = \text{Max} \int_{T_1}^{T_2} \left( \frac{C^{1-\delta}}{1-\delta} + \frac{E_2^{1-\delta}}{1-\delta} \right) e^{-\rho(t-T_1)} + V_3 * e^{-\rho T_2} \\ \text{st} \begin{cases} \dot{K} = \alpha_2(1 - \phi)K - C \\ \dot{S} = -\xi(E_1 + E_2). \end{cases} \end{aligned}$$

The resolution of the equation of capital accumulation using FOCs gives (see proof in Appendix C):

$$K_t = -(\bar{K}_2 - K_{T_1}) * e^{(\frac{\alpha_2(1-\phi)-\rho}{\delta})(t-T_1)} + \bar{K}_2,$$

where  $\bar{K}_2$  is unknown and will be determined by using boundary conditions in Section 3.1.4. Finally, by using the fact that the NRE is exhaustible and the fact that we have crossed the second pollution regime after a period of time  $T_1$ , we get (see proof in Appendix D):

$$\lambda_{2.T_1} = \frac{1}{\xi} \left[ \left( \frac{-S_0 + \bar{Z}}{\xi} + \frac{\alpha_2(1-\phi)}{\beta_2} \bar{K}_2 (T_2 - T_1) - \frac{\alpha_2(1-\phi)\delta}{\beta_2(\alpha_2(1-\phi)-\rho)} (\bar{K}_1 - K_0) e^{\frac{\alpha_2(1-\phi)-\rho}{\delta} T_1} * \left[ e^{\frac{\alpha_2(1-\phi)-\rho}{\delta} * (T_2 - T_1)} - 1 \right] \frac{\rho}{\delta [e^{-\frac{\rho}{\delta} T_1} - 1]} \right]^{-\delta}, \right.$$

where  $\lambda_{2.T_1}$ ,  $K_{T_1}$  and  $\bar{K}_2$  are unknown that will be determined by boundary conditions in Section 3.1.4.

### 3.1.3 First energy regime (NR, $\underline{Z}$ )

At the beginning of the programme, the economy starts using both energy sources and faces a pollution accumulation constraint. A catastrophic event may happen as soon as

the level of pollution reaches its critical threshold that results in a loss of capital during the following two regimes. We assume that the NRE is abundant ( $S_0 > \bar{Z}$ ) so that we do not need to consider the accumulation of the NRE during the first regime. Therefore, the economy crosses the pollution threshold before the complete depletion of the NRE. The social planner maximizes the sum of the discounted pre-event utilities and the discounted value function of the second regime subject to the constraint on capital accumulation and on pollution accumulation. As we do not take into account the regeneration capacity of the environment, the equation of the pollution accumulation can be expressed as the opposite of that of the NRE:  $\dot{Z} = -\dot{S} = \xi(E_1 + E_2)$ .

The social planner solves:

$$V_1 = \text{Max} \int_0^{T_1} \left[ \left( \frac{C^{1-\delta}}{1-\delta} + \frac{E_2^{1-\delta}}{1-\delta} \right) e^{-\rho t} \right] dt + V_2^* e^{-\rho T_1}$$

$$\text{st} \begin{cases} \dot{K} &= \alpha_2(1-\phi)K - C \\ \dot{Z} &= \xi(E_1 + E_2). \end{cases}$$

The FOCs give (see proof in Appendix E):

$$\dot{K} - \alpha_2(1-\phi)K = -\lambda_{1,0}^{-\frac{1}{\delta}} e^{(\frac{\alpha_2(1-\phi)-\rho}{\delta})t}.$$

We solve the above equation to get:

$$K_t = -(\bar{K}_1 - K_0) e^{(\frac{\alpha_2(1-\phi)-\rho}{\delta})t} + \bar{K}_1.$$

Finally, we use the fact that at the end of the first regime we cross the pollution threshold, and we obtain:

$$\frac{1}{\xi} \bar{Z} = -(-\lambda_{2,0} \xi)^{-\frac{1}{\delta}} * \frac{\delta}{\rho} [e^{-\frac{\rho}{\delta} T_1} - 1] + \frac{\alpha_2(1-\phi)}{\beta_2} \bar{K}_1 * T_1 - \frac{\alpha_2(1-\phi)\delta}{\beta_2(\alpha_2(1-\phi)-\rho)} (\bar{K}_1 - K_0) \left[ e^{(\frac{\alpha_2(1-\phi)-\rho}{\delta}) * T_1} - 1 \right].$$

This implies that:

$$\lambda_{2,0} = -\frac{1}{\xi} \left[ \left( -\frac{\bar{Z}}{\xi} + \frac{\alpha_2(1-\phi)}{\beta_2} \bar{K}_1 * T_1 - \frac{\alpha_2(1-\phi)\delta}{\beta_2(\alpha_2(1-\phi)-\rho)} (\bar{K}_1 - K_0) [e^{(\frac{\alpha_2(1-\phi)-\rho}{\delta}) * T_1} - 1] \right) * \frac{\rho}{\delta [e^{-\frac{\rho}{\delta} T_1} - 1]} \right]^{-\delta},$$

where  $\lambda_{2,0}$  and  $\bar{K}_1$  are unknown and will be determined in Section 3.1.4 using boundary conditions.

### 3.1.4 Boundary conditions

Following Boucekkine et al. (2013), we use three types of boundary conditions: (i) continuity of  $\lambda_1$ ; (ii) continuity of  $K$ ; and (iii) the equality of the Hamiltonian at the switching time. The co-state variable  $\lambda_2$  associated with the pollution stock  $Z$  is not continuous at the switching time  $T_1$  because  $Z$  is fixed to  $\bar{Z}$ . At the switching time  $T_2$ ,  $Z$  can be freely chosen and becomes continuous but it no longer exists during the third regime because the RE is not polluting. The continuity of  $\lambda_1$  together with that of  $K$  helps to determine  $\bar{K}_1$ ,  $\bar{K}_2$ ,  $K_{T_1}$ ,  $K_{T_2}$ ,  $\lambda_{T_2}$ ,  $\lambda_{2,0}$  and  $\lambda_{2,T_1}$  (Proof available upon request). We then simultaneously and numerically solve the equality of Hamiltonians at the switching time  $T_1$  and  $T_2$  to get  $T_1$  and  $T_2$ . Now, let us look at the corner regimes before providing the numerical value function.

## 3.2 Corner regimes

As we exclude four corner regimes among a total of eight corners regimes because they are unfeasible, in this section we present only the four relevant ones.

### 3.2.1 Sole switch to the energy regime ( $T_1=\infty$ )

This case is a corner regime in which the economy never exceeds the critical pollution threshold and therefore only switches to the sole adoption of clean energy. The economy starts using both oil and the renewable resource that are complementary, and the pollution is below its critical level. After some time  $T$ , it switches to the sole use of renewable energy before the level of pollution crosses the pollution threshold. Therefore, the economy escapes the catastrophe forever. To get the switching time  $T$ , it is sufficient to set  $T_1=\infty$  and  $T_2 = T$ .

### 3.2.2 Sole switch above the pollution threshold level ( $T_2=\infty$ )

This case corresponds to the transition from the first regime to the second regime without the switch to the third regime. Again, the economy starts using both oil and the renewable source of energy with a level of pollution that is below the threshold level. Then, the economy switches to the regime in which both energy sources are still used but, the level of pollution is now above its critical threshold and the economy never adopts the renewable energy. To get the switching time  $T$  and the dynamics of variables, one needs to set  $T_2=\infty$  and  $T_1 = T$ .

### 3.2.3 No switch ( $T_1=\infty$ and $T_2=\infty$ )

On the no switch transition path, the economy always uses both oil and the renewable source of energy. Moreover, it never solely uses the RE and the level of pollution remains below its critical threshold forever. This energy transition path corresponds to the first regime and one does not need to use boundary conditions to get the switching time. It is sufficient to set  $T_1=\infty$  and use the transversality conditions that give  $\bar{K}_1 = 0$ .

### 3.2.4 Starting with RE ( $T_1=\infty$ and $T_2=0$ )

On this transition path, the economy never uses the NRE and therefore does not pollute. The pollution threshold then becomes irrelevant. It corresponds to the third regime without any pollution threat. In this case, we need to set  $T_1=\infty$  and  $T_2=0$ .

## 4 Numerical results

In this section, we numerically solve for the switching times  $T_1$  and  $T_2$ , and calculate the value functions of the general energy path and that of each corner regimes. We present the parameter values that are used to get the numerical results. We also provide the numerical value functions and the sensitivity analysis.

## 4.1 Parameter values

The parameter values are chosen as follows. As we are concerned about environmental issues (pollution) that can lead to a catastrophic event, we set the discount rate  $\rho$  to 0.05, so that people are more patient and concerned about the consequences of their behaviour in the future. This value of 0.05 is standard in the economics literature. The sensitivity analysis will help to show how the pollution could evolve in the case where people are impatient (high discount factor). We consider an initial stock of the NRE  $S_0$  equals to 28000 and the pollution threshold  $\bar{Z} = 1000$  as a benchmark. In the final goods sector, we set the parameter  $\alpha_2$  that is related to capital to 0.0001 and that of energy  $\beta_2$  to 0.02 in the Leontief function. As we are concerned about energy issues, we focus on energy-intensive final goods. The factor of capital transformation into energy  $\varphi$  is set to 1.5. This coefficient is higher than one so that one unit of capital produces more than one unit of clean energy. We also assume that to get one unit of energy services, the economy should provide 1.5 units of the NRE such that  $\xi=1.5$ . The part of capital that is lost due to the catastrophe  $\theta$  is set to 0.05. The value of the degree of relative risk aversion  $\delta$  and that of the initial level of capital are set to 2 and 95, respectively. Finally, we take  $\phi=0.1$ .

We compare the value functions among them and choose the optimal one that gives the highest value function. We also perform a sensitivity analysis to check for the impact of each parameter on the switching time.

## 4.2 Value functions

The numerical results are summarized in the table below.

Energy transition path	values functions
General energy transition path	-36.7722
$T_1=\infty$ ,	-42.4142
$T_2=\infty$	<b>-17.6568</b>
$T_1=\infty$ and $T_2=\infty$	-19.2455
$T_1=\infty$ and $T_2=0$	-50.8961

**Table 1:** Numerical results

The optimal energy transition path is the one that gives the highest value function to the planner. It corresponds to  $T_2=\infty$  corner regime. It means that the optimal energy transition path can be described as follows. The economy starts using both sources of energy. Then, it crosses the pollution threshold and loses a part of its capital. Finally, the sole adoption of the renewable energy is optimal only in the long run. One could observe that the corner regime that corresponds to  $T_1=\infty$  and  $T_2=\infty$  case is close to that of the optimal one. This may be justified by the fact that the economy does not lose or gain enough by refraining to pollute more in order to never cross the pollution threshold. One could also remark that the general energy transition path is far from being the optimal one. Hence, we can conclude that there exist parameters that imply that it is not optimal to only adopt RE. This surprising result goes in line with the asymptotic energy transition arguments that state that the complete transition to the sole use of clean energy may happen only in the long run. It may be a consequence of

the impossibility of self-reproducing renewable energy. As the economy still needs fossil fuels to produce clean energy, it is efficient to progressively replace fossil fuels with a clean source of energy. Then, a quick and full energy transition is not optimal for the economy, and one should not expect any immediate transition to an economy that only uses renewable sources of energy.

### 4.3 Sensitivity analysis

We summarize the sensitivity analysis in the table below.

	$\rho$	$\theta$	$S_0$	$\alpha_2$	$\beta_2$	$\bar{Z}$
$T_1$	-	+	small effect	+	+	+

**Table 2:** Sensitivity analysis

Sensitivity analysis shows that the optimal time to cross the pollution threshold positively depends on: (i) the corresponding capital loss; (ii) the productivity of capital and energy services; and (iii) the level of the pollution threshold. Moreover, it negatively depends on the discount rate.

The more impatient social planner is willing to extract more NRE and will quickly cross the critical pollution threshold. As the damage from the catastrophic event is high, people will fear the negative consequences of their "dirty" energy use and will reduce it. This could help them to stay longer in the first regime before crossing the pollution threshold. This suggests that the economy that fears the negative consequences of climate change and the risk of ecological catastrophe is more favorable to the energy transition. In terms of policy implications, people must be more sensitized about the potential consequences of their use of fossil fuels.

Likewise, people will reduce their use of energy resource as long as the productivity of capital and energy services is high. Therefore, public policies should promote investments in energy innovation that targets productive sector, home appliances and buildings and helps to save both money and energy. The higher the pollution threshold that could provoke the catastrophic event, the more people will stay in the pre-event regime. Finally, the initial stock of the NRE does not matter. The social planner mainly cares about the management of the initial stock of the NRE so that the switching time  $T_1$  is robust with respect to the initial stock of the NRE.

## 5 Introducing investment in Energy Saving Technologies (EST)

Let us recall that  $E_1$  and  $E_2$  are energy services in the final goods sector and for households respectively. The final goods sector uses  $E_{1s}$  of the NRE and  $E_{1x}$  of the RE, while households use  $E_{2s}$  of the NRE and  $E_{2x}$  of the RE. At each period of time, in addition to consumption and investments in energy sector and final goods sector, the economy now invests a part of the final goods production  $q_t$  in energy saving technologies. We assume

that the investment  $q_t$  serves to reduce by  $\vartheta(q)$  units the resources that the economy needs in order to get the same energy services. Implicitly, it means that we do not account for a scale effect.<sup>2</sup> Let us assume that  $\vartheta(q)$  is an increasing function ( $\vartheta'(q) > 0$ ) and exhibits decreasing marginal returns ( $\vartheta''(q) < 0$ ) in the abatement investment.  $\vartheta(q)$  is increasing in the sense that the more the economy invests in EST, the more it reduces the use of the energy resource to get a given energy service. Moreover, as  $\vartheta(q)$  is increasing, we assume that  $\vartheta(q)$  is concave in order to have a maximum for  $\vartheta(q)$ . Also, we avoid a complete elimination of the use of energy resources so that it will require an infinite amount of investment to do so ( $\lim_{q \rightarrow \infty} E_i - \vartheta(q) = 0$  with  $i \in \{1, 2\}$  and  $\vartheta(0) = 0$ ).

Due to the investment  $q_t$  in energy saving technologies, the dynamics of capital, of the NRE and that of pollution are modified, while the utility of the household remains the same (Proof available upon request). Note that those dynamics do not change in terms of the extraction of energy resource, but only in terms of the energy services. The same amount of energy resource provides more energy services when the energy saving technologies are used. In comparison with the previous model, the social planner has to consider one additional control variable (investment  $q_t$ ) to solve for the optimal energy transition. The main changes in the results are the following (Proof available upon request). The level of capital at each period of time during the three regimes has an additional negative component. In fact, the economy additionally uses a part of its income to invest in EST. This part could have been invested in productive sector (final goods and energy) or consumed by households. As the share of the income that goes to investment is reduced by investment in energy saving technologies, one should expect a decrease in capital.

As before, we also discuss corner regimes that we compare to the general energy transition path to isolate the optimal one. In order to make our numerical results comparable, we use the same set of parameter values as before. Additionally, we set the productivities of investment in EST both at the household level and at industry level  $\sigma$  to 0.2. We numerically solve for the switching times  $T_1$  and  $T_2$  and calculate the value functions of the general energy path and that of each corner regimes. We compare the value functions among them and find out the optimal one that gives the highest value function. We also perform a sensitivity analysis to check for the impact of each of the parameters on the switching times. The numerical results are threefold. First, investments in energy saving technologies do not alter the optimal energy transition path which remains the asymptotic transition to the sole use of renewable energy. The second result is that investments in energy saving technologies increase the time at which the economy may experience the catastrophe and that of the sole adoption of the renewable energy. In fact, investments in energy saving technologies help to reduce the consumption of energy for the same quality of energy services and therefore help to reduce the pollution. Although investment in EST reduces the share of the income that goes to investment in both the final goods sector and the renewable energy production sector,

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<sup>2</sup>One should also consider that the investment  $q_t$  induces a scale effect. This makes the present model very complex and unsolvable because of the interaction that may appear between  $q_t$  and all the precedent control variables like the energy services.

it favours the energy transition. Last but not least, investment in EST increases the welfare of the society. Then, it is profitable for the economy to combine both adoption of renewable energy and investments in energy saving technologies.

## 6 Conclusion

This paper makes three contributions. First, it proposes a general appraisal of optimal switching problems of energy transition exhibiting: (i) the possibility of a catastrophe due to pollution accumulation; and (ii) technological regimes with the adoption of renewable energy. Second, it numerically shows that the optimal energy transition path may correspond to a corner regime in which the economy starts using both resources, crosses the pollution threshold by losing a part of its capital and never adopts a regime with only renewable energy. This result is in line with the asymptotic energy transition argument stating that the transition to a clean energy may happen only in the long run. We also show that economy reduces the use of energy resource as long as the productivity of capital and energy services is high. Therefore, public policies should promote investments in energy innovation that targets productive sector, home appliances and buildings and helps to save both money and energy. The third contribution of this paper is to extend this model to the adoption of energy saving technologies. We mainly find that investments in energy saving technologies do not alter the optimal energy transition path. Moreover, investments in energy saving technologies favour energy transition in the sense that it increases the time at which the economy may experience the catastrophe and that of the sole adoption of the renewable energy. Finally, as investment in EST increases the welfare of the society, it is then profitable to combine both adoption of renewable energy and investments in energy saving technologies. However, investments in EST reduce the share of the income that goes to investment in both the final goods sector and the renewable energy production sector.

In terms of policy implications, we recommend that it is important to adopt some economic instruments such as taxes on the "dirty" energy, subsidies on the "clean" energy, or incentives for energy saving technologies in order to promote the energy transition. Also, it is profitable to design economic instruments that jointly target the promotion of "clean" energy and incentives for investments in energy saving technologies. This is particularly important for developing countries that mostly rely on polluting energy resources and are the most vulnerable to climate change. But those economic instruments should be designed to meet the requirements of a transition to a sole use of "clean" energy in the long run. In fact, as a quick and full transition is not optimal for the economy, we should not expect any immediate transition to an economy that only uses renewable sources of energy. This paper can be extended to investigate the optimal taxes/subsidies that may favour the adoption of renewable energy and the investments in energy saving technologies in line with the asymptotic energy transition result.



## 7 Appendix

### 7.1 Appendix A

Let us recall that the equation of capital accumulation is:

$$\dot{K}_t = Y_t - C_t. \quad (17)$$

We also know that:  $Y = \min\{\alpha_2 K_2, \beta_2 E_{1t}\}$ , where,  $K = K_1 + K_2$  and  $E_x = \varphi K_1$ .  $E_x = \varphi K_1$  implies that  $K_1 = \frac{E_x}{\varphi}$ . Then,

$$K_2 = K - K_1 = K - \frac{E_x}{\varphi}. \quad (18)$$

From "Leontief conditions" in final goods sector, we have that:

$$Y = \alpha_2 K_2 = \beta_2 E_{1t}. \quad (19)$$

During the third regime, only the RE is used so that we have the following equalities:  $E_{1xt} = E_{1t}$ , and  $E_{2xt} = E_{2t}$ . By summing up the above two expressions and plugging it into successively (18), (19) and into (17) gives  $\dot{K}_t = \alpha_2 K_t - \alpha_2 \frac{E_{1t} + E_{2t}}{\varphi} - C_t$ .

### 7.2 Appendix B

To determine the expression of capital in the third regime, we need to solve the following equation of capital accumulation for the capital  $K_t$ :  $\dot{K} = \Lambda K - \Theta \lambda_{T_2}^{-\frac{1}{\delta}} e^{(\frac{\alpha_2 - \rho}{\delta})(t - T_2)}$ , where  $\Lambda = \frac{\alpha_2 \beta_2 \varphi}{\alpha_2 + \beta_2 \varphi}$  and  $\Theta = \frac{\alpha_2 \beta_2}{\alpha_2 + \beta_2 \varphi} \left(\frac{\alpha_2}{\varphi}\right)^{-\frac{1}{\delta}} + 1$ . By making a change of variables as follows  $x = K e^{-\Lambda(t - T_2)}$  and using the following transversality conditions  $\lim_{t \rightarrow \infty} \lambda_t K_t e^{-\rho(t - T_2)} = 0$ , we get that  $K_t = -\frac{\Theta \delta}{\alpha_2 - \rho - \delta \Lambda} \lambda_{T_2}^{-\frac{1}{\delta}} e^{(\frac{\alpha_2 - \rho}{\delta})(t - T_2)}$ , for  $\alpha_2(1 - \delta) < \rho$ .

### 7.3 Appendix C

The expression of capital in the second regime is determined from FOCs as follows.

FOCs lead to:  $\lambda_1 = \lambda_{1.T_1} e^{(\rho - \alpha_2(1 - \phi))(t - T_1)}$ ,  $\lambda_2 = \lambda_{2.T_1} e^{\rho(t - T_1)}$ ,  $C_t = \lambda_{1.T_1}^{-\frac{1}{\delta}} e^{(\frac{\alpha_2(1 - \phi) - \rho}{\delta})(t - T_1)}$  and  $E_{2t} = (\xi \lambda_{2.T_1})^{-\frac{1}{\delta}} e^{-\frac{\rho}{\delta}(t - T_1)}$ . By using the above expression of C, the equation of capital accumulation becomes:  $\dot{K} - \alpha_2(1 - \phi)K = -\lambda_{1.T_1}^{-\frac{1}{\delta}} e^{(\frac{\alpha_2(1 - \phi) - \rho}{\delta})(t - T_1)}$ . Using the same variable change as in Appendix B and taking  $K_t$  at  $t = T_1$ , give:

$K_t = -(\overline{K_2} - K_{T_1}) * e^{(\frac{\alpha_2(1 - \phi) - \rho}{\delta})(t - T_1)} + \overline{K_2}$ , where  $\overline{K_2}$  is unknown and will be determined by using boundary conditions in Section 3.1.4.

## 7.4 Appendix D

We assume that the NRE is exhaustible and that we have crossed the second regime after a period of time  $T_1$ . Then, the initial stock of the NRE  $S_0$  is equal to the sum of the part of the NRE that is used during the first regime which corresponds to the total amount of pollution  $\bar{Z}$  and the part of the NRE that the economy uses during the second regime. We have that:  $S_0 = \underbrace{\int_0^{T_1} \xi(E_{1t} + E_{2t})dt}_{\bar{Z}} + \int_{T_1}^{T_2} \xi(E_{1t} + E_{2t})dt$ . This implies that:

$$S_0 - \bar{Z} = \int_{T_1}^{T_2} \xi(E_{1t} + E_{2t})dt = \frac{\xi\alpha_2}{\beta_2} \int_{T_1}^{T_2} K_t dt + \xi \int_{T_1}^{T_2} E_{2t} dt, \text{ with } S_0 > \bar{Z}.$$

The above equation gives:

$$\frac{1}{\xi}(S_0 - \bar{Z}) = -(\xi\lambda_{2,T_1})^{-\frac{1}{\delta}} * \frac{\delta}{\rho} [e^{-\frac{\rho}{\delta}(T_2-T_1)} - 1] + \frac{\alpha_2(1-\phi)\bar{K}_2}{\beta_2} [(T_2 - T_1)] - \frac{\delta\alpha_2}{\beta_2(\alpha_2(1-\phi)-\rho)} * (\bar{K}_2 - K_{T_1}) * [e^{(\frac{\alpha_2(1-\phi)-\rho}{\delta})(T_2-T_1)} - 1].$$

## 7.5 Appendix E

The level of capital at each time during the first regime is determined as follows.

FOCs give:  $\lambda_1 = \lambda_{1,0}e^{(\rho-\alpha_2(1-\phi))t}$ ,  $\lambda_2 = \lambda_{2,0}e^{\rho t}$ ,  $C_t = \lambda_{1,0}^{-\frac{1}{\delta}}e^{(\frac{\alpha_2(1-\phi)-\rho}{\delta})t}$  and  $E_{2t} = (-\lambda_{2,0}\xi)^{-\frac{1}{\delta}}e^{-\frac{\rho}{\delta}t}$ . As before, we also replace the expression of  $C$  into the equation of capital accumulation to get:  $\dot{K} - \alpha_2(1-\phi)K = -\lambda_{1,0}^{-\frac{1}{\delta}}e^{(\frac{\alpha_2(1-\phi)-\rho}{\delta})t}$ . Solving the above equation and taking  $K_t$  at  $t = 0$  give  $K_t = -(\bar{K}_1 - K_0)e^{(\frac{\alpha_2(1-\phi)-\rho}{\delta})t} + \bar{K}_1$ . Finally, at the end of the first regime, we cross the pollution threshold so that  $\bar{Z} = \int_0^{T_1} \xi(E_{1t} + E_{2t})dt$ . This equation then implies that:

$$\lambda_{2,0} = -\frac{1}{\xi} \left[ \left( -\frac{\bar{Z}}{\xi} + \frac{\alpha_2(1-\phi)}{\beta_2} \bar{K}_1 * T_1 - \frac{\alpha_2(1-\phi)\delta}{\beta_2(\alpha_2(1-\phi)-\rho)} (\bar{K}_1 - K_0) [e^{(\frac{\alpha_2(1-\phi)-\rho}{\delta}) * T_1} - 1] \right) * \frac{\rho}{\delta[e^{-\frac{\rho}{\delta}T_1} - 1]} \right]^{-\delta}$$

where  $\lambda_{2,0}$  and  $\bar{K}_1$  are unknown and will be determined in Section 3.1.4 using boundary conditions.

## 8 References

- [1] Acemoglu, D., Akcigit, U., Hanley, D., Kerr, W., 2014. The transition to clean technology. MIT Department of Economics, Working Paper.
- [2] Amigues J.P., Ayong Le Kama A., Chakravorty U., Moreaux M., 2013. Equilibrium Transitions from Non Renewable Energy to Renewable Energy under Capacity Constraints. TSE Working Paper, 13-440.
- [3] Ayong Le Kama, A., Pommeret, A., Prieur, F., 2011. Optimal emission policy under the risk of irreversible pollution. Nota di lavoro/Fondazione Eni Enrico Mattei: Sustainable development.
- [4] Berndt, E. R., Wood, D. O., 1975. Technology, prices, and the derived demand for energy. The review of Economics and Statistics, 259-268.

- [5] Boucekkine, R., Pommeret, A., 2004. Energy saving technical progress and optimal capital stock: the role of embodiment. *Economic Modelling* 21(3), 429-444.
- [6] Boucekkine, R., Pommeret, A., Prieur, F., 2013. Optimal regime switching and threshold effects. *Journal of Economic Dynamics and Control* 37(12), 2979-2997.
- [7] Chakravorty, U., Leach, A., Moreaux, M., 2012. Cycles in non renewable resource prices with pollution and learning-by-doing. *Journal of Economic Dynamics and Control* 36 (10), 1448–1461.
- [8] Chakravorty, U., Magné, B., Moreaux, M., 2006. A Hotelling model with a ceiling on the stock of pollution. *Journal of Economic Dynamics and Control* 30(12), 2875–2904.
- [9] Chakravorty, U., Moreaux, M., Tidball, M., 2008. Ordering the extraction of polluting non renewable resources. *The American Economic Review* 98(3), 1128–1144.
- [10] Chakravorty, U., Roumasset, J., Tse, K., 1997. Endogenous substitution among energy resources and global warming. *Journal of Political Economy*, 105(6), 1201-1234.
- [11] Charlier, D., Mosino, A., Pommeret, A., 2011. Energy-saving technology adoption under uncertainty in the residential sector. *Annals of Economics and Statistics/Annales d'Économie et de Statistique*, 43-70.
- [12] Clarke, H. R., Reed, W. J., 1994. Consumption/pollution tradeoffs in an environment vulnerable to pollution-related catastrophic collapse. *Journal of Economic Dynamics and Control*, 18(5), 991-1010.
- [13] Cropper, M. L., 1976. Regulating activities with catastrophic environmental effects. *Journal of environmental Economics and Management*, 3(1), 1-15.
- [14] Dasgupta, P., Heal, G., 1979. *Economic theory and exhaustible resources*. Cambridge University Press.
- [15] Dasgupta, P., Heal, G., 1974. The optimal depletion of exhaustible resource. *The Review of Economic Studies* 41, 3-28.
- [16] Dasgupta, P., Stiglitz, J., 1981. Resource depletion under technological uncertainty. *Econometrica: Journal of the Econometric Society*, 85-104.
- [17] De Groot, H. L., Verhoef, E. T., Nijkamp, P., 2001. Energy saving by firms: decision-making, barriers and policies. *Energy Economics* 23(6), 717-740.
- [18] Díaz, A., Puch, L. A., 2013. A Theory of Vintage Capital Investment and Energy Use. Working paper, Documentos de Trabajo del Instituto Complutense de Análisis Económico (ICAE) 35,23330.
- [19] Forster, B., A., 1975. Optimal pollution control with a nonconstant exponential rate of decay. *Journal of environmental Economics and Management*, 2(1), 1-6.
- [20] GEA, 2012. *Global Energy Assessment- Toward a Sustainable Future*. Cambridge University Press, Cambridge UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria.
- [21] Gjerde, J., Grepperud, S., Kverndokk, S., 1999. Optimal climate policy under the possibility of a catastrophe. *Resource and Energy Economics*, 21(3), 289-317.
- [22] Golosov, M., Hassler, J., Krusell, P., Tsyvinski, A., 2011. Optimal taxes on fossil fuel in general equilibrium. Working paper, National Bureau of Economic Research.
- [23] Horii, R., Ikefuji, M., 2010. Natural disasters in a two-sector model of endogenous growth. Center Discussion Paper, Economic Growth Center.
- [24] Karp, L., Tsur, Y., 2011. Time perspective and climate change policy. *Journal of Environmental Economics and Management*, 62(1), 1-14.

- [25] Kollenbach, G., 2013. Endogenous Growth with a Ceiling on the Stock of Pollution. Working paper, MPRA.
- [26] Krautkraemer, J., A., 1998. Nonrenewable resource scarcity. *Journal of Economic Literature*, 2065-2107.
- [27] Lafforgue, G., Magné, B., Moreaux, M., 2008. Optimal Sequestration Policy with a Ceiling on the Stock of Carbon in the Atmosphere. Working paper No. 401. Institut d'Économie Industrielle (IDEI), Toulouse.
- [28] Nævdal, E., 2006. Dynamic optimization in the presence of threshold effects when the location of the threshold is uncertain – with an application to a possible disintegration of the western antarctic ice sheet. *Journal of Economic Dynamics and Control* 30, 1131–1158.
- [29] Nordhaus, W., D., 1994. Managing the global commons: the economics of climate change. Cambridge, MIT press, 101-120.
- [30] Pelli M., 2012. The Elasticity of Substitution between Clean and Dirty Inputs in the Production of Electricity. Mimeo, University of Alberta.
- [31] Pindyck, R. S., 2002. Optimal timing problems in environmental economics. *Journal of Economic Dynamics and Control* 26.9, 1677-1697.
- [32] Pindyck, R. S., Rotemberg, J. J., 1983. Dynamic factor demands and the effects of energy price shocks. *The American Economic Review*, 1066-1079.
- [33] Pommeret, A., Prieur, F., 2009. Double irreversibility and environmental policy design. Working paper, No. 2009.10.
- [34] Prieur, F., 2007. The Environmental Kuznets Curve in a World of Irreversibility. Working paper, Nota di Lavoro, Fondazione Eni Enrico Mattei, No. 57.2007.
- [35] Prieur, F., Tidball, M., Withagen, C., 2013. Optimal emission-extraction policy in a world of scarcity and irreversibility. *Resource and Energy Economics* 35(4), 637-658.
- [36] Tahvonen, O., 1996. Trade with Polluting Non renewable Resources. *Journal of Environmental Economics and Management* 30, 1-17.
- [37] Tahvonen, O., 1997. Fossil Fuels, Stock Externalities, and Backstop Technology. *The Canadian Journal of Economics* 30, 855-874.
- [38] Tahvonen, O., Withagen, C., 1996. Optimality of irreversible pollution accumulation. *Journal of Economic Dynamics and Control* 20(9), 1775-1795.
- [39] Tsur, Y., Withagen, C., 2013. Preparing for catastrophic climate change. *Journal of Economics* 110(3), 225-239.
- [40] Tsur, Y., Zemel, A., 1996. Accounting for global warming risks: resource management under event uncertainty. *Journal of Economic Dynamics and Control*, 20(6), 1289-1305.
- [41] Tsur, Y., Zemel, A., 2003. Optimal transition to backstop substitutes for nonrenewable resources. *Journal of Economic Dynamics and Control*, 27.4, 551-572.
- [42] Tsur, Y., Zemel, A., 2005. Scarcity, growth and R&D. *Journal of Environmental Economics and Management* 49(3), 484-499.
- [43] Ulph, A., Ulph, D., 1997. Global warming , irreversibility and learning. *The Economic Journal*, 107(442), 636-650.
- [44] Van der Ploeg, F., Withagen, C., 2012. Is there really a Green Paradox?. *Journal of Environmental Economics and Management* 64(3), 342-363.

[45] Van der Ploeg, F., Withagen, C., 2014. Growth, renewables, and the optimal carbon tax. *International Economic Review*, 55.1, 283-311.